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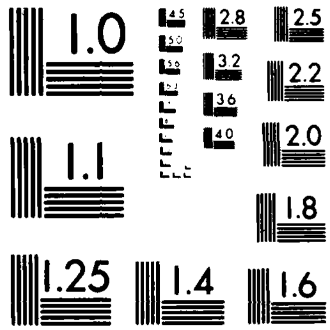
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The reason for developing a low-voltage short-wavelength FEL is given. Constraints imposed by electron energy spread require that the second stage of a two-stage FEL have a relatively long wavelength pump field ($\geq$ 1 mm) of very high intensity ($\sim 10^8$ W/cm^2). A quasioptical cavity concept has been developed to produce such a field. A helical wiggler is needed to excite the TE_{01} waveguide mode in this cavity. Work is described on the development of a permanent magnet helical wiggler for this system. Off-axis electron trajectories in the wiggler that couple to the TE_{01} mode are identified, and a microwave cold test laboratory to

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measure losses in a quasioptical cavity is described. A planned experiment to test the first-stage system design is also described.

KMSF-U1526

Annual Summary Report

for

1 October 1983 through 30 September 1984

for

Contract N00014-80-C-0614

Two-Stage Free Electron Laser Research

Principal Investigator - Stephen B. Segall

KMS Fusion, Inc., P. O. Box 1567, Ann Arbor, MI 48106

October 24, 1984

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I. Description of the Problem

KMS Fusion, Inc. began studying the feasibility of two-stage free electron lasers for the Office of Naval Research in June, 1980. At that time, the two-stage FEL was only a concept that had been proposed by Luis Elias.[1] The range of parameters over which such a laser could be successfully operated, attainable power output, and constraints on laser operation were not known. The primary reason for supporting this research at that time was that it had the potential for producing short-wavelength radiation using a relatively low voltage electron beam.

One advantage of a low-voltage two-stage FEL would be that shielding requirements would be greatly reduced compared with single-stage short-wavelength FEL's. If the electron energy were kept below about 10 MeV, x-rays, generated by electrons striking the beam line wall, would not excite neutron resonances in atomic nuclei. These resonances cause the emission of neutrons with subsequent induced radioactivity. Therefore, above about 10 MeV, a meter or more of concrete shielding is required for the system, whereas below 10 MeV, a few millimeters of lead would be adequate.

In evaluating the feasibility of the two-stage FEL, the parameter range over which the laser could operate had to be determined. The primary limitation on operation of the second stage was found to be energy spread and voltage stability of the electron beam. It is desirable that the energy spread not exceed the full bucket height for efficient laser operation. The full bucket height, $\Delta\gamma_b$, for a second stage with an electromagnetic pump field of wavelength λ_p is given in mks units by

$$\Delta\gamma_b = \frac{e\lambda_p}{\pi mc^2} (E_L E_p)^{1/2} , \tag{1}$$

where E_L and E_p are the electric fields of the second-stage laser and pump beams, respectively. For circularly-polarized light, intensity is given by

$$I = \epsilon_0 c E^2 , \tag{2}$$

and for an electromagnetic pump field the laser wavelength is given by

$$\lambda_L = \lambda_p / 4\gamma^2 . \tag{3}$$

The relative electron energy spread, $\Delta\gamma/\gamma$, should, therefore, not exceed

$$\frac{\Delta\gamma_b}{\gamma} = \frac{2e}{\pi mc^2} \left(\frac{\lambda_L \lambda_P}{\varepsilon_0 c}\right)^{1/2} (I_L I_P)^{1/4} . \qquad (4)$$

Figure 1 gives the value of $\Delta\gamma_b/\gamma$ as a function of pump-field intensity for a range of pump-field wavelengths, assuming a second-stage laser wavelength of 1 μm and a second-stage laser intensity of 1 kW/cm^2.

Two techniques for producing short-wavelength radiation were originally under consideration: one using a high-current low-energy beam from a diode-type accelerator to convert CO_2-laser radiation from 10μm to 1μm, and a second experiment using an electrostatic accelerator at UCSB to convert far-infrared radiation to near-infrared radiation. The CO_2 upconversion experiment is clearly not technically feasible (see Figure 1), because the energy spread required is orders of magnitude lower than could be achieved with the proposed accelerators. Two-stage operation did appear feasible using an electrostatic accelerator, which has the smallest energy spread and beam emittance of all types of accelerators, except possibly storage rings operating without an FEL. Great care has been taken to design the UCSB accelerator to minimize energy spread and beam emittance. An effective energy spread of $\sim 10^{-4}$ is expected from this device.

One conclusion that can be drawn from Figure 1 is that to perform a successful two-stage FEL experiment using the UCSB electrostatic accelerator first-stage laser intensities of at least 10^8 - 10^9 W/cm^2 will be needed.

Assuming the energy spread is acceptable and the required first-stage intensity can be achieved, it must still be established that laser gain would be adequate to sustain second-stage oscillation. The highest gain that can be achieved in an FEL is small signal gain. In order to operate the second stage, the small signal gain would have to be at least several percent.

Small signal gain obtained from a one-dimensional model of the FEL is given approximately in mks units by[2]

$$G_{max} \approx 3.5 \times 10^{-14} I_p J_e \lambda_p \left(\frac{L_p}{\gamma}\right)^3$$

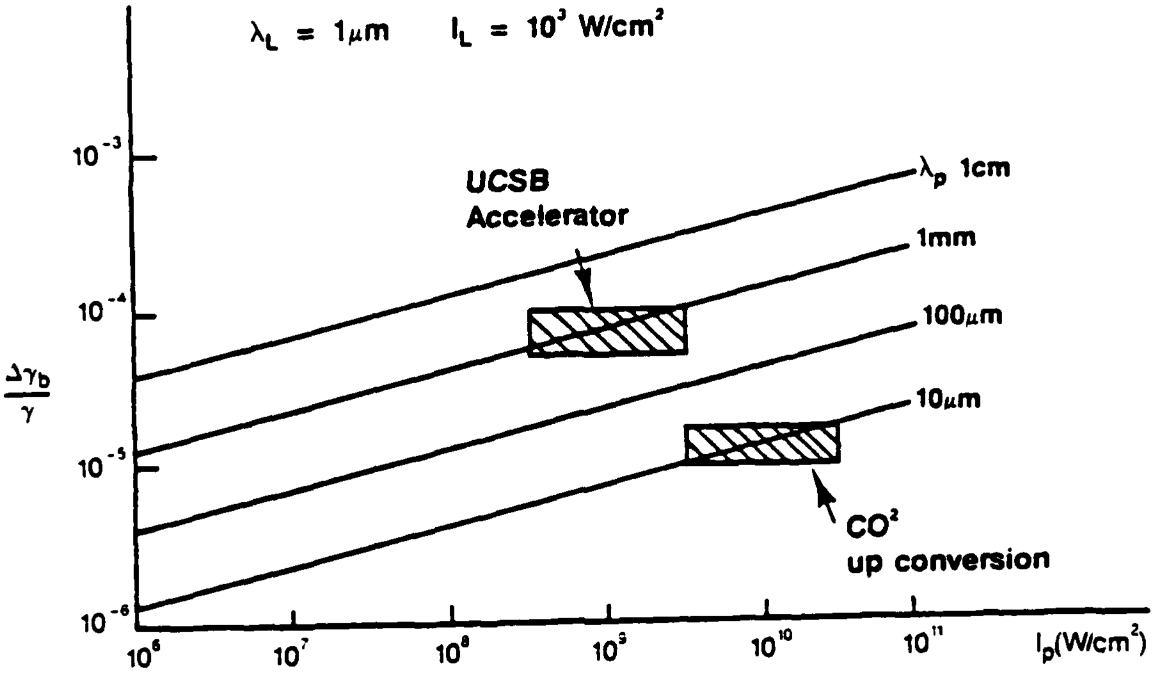

Figure 1. Permissible electron beam energy spread for two-stage FEL operation.

where J_e is the electron current density and L_p is the length of the second stage interaction region. Assuming a 1-mm-wavelength pump field is used to produce 5-μm radiation, then $\gamma = 7.1$, corresponding to an electron beam energy of 3.1 MeV. Figure 2 shows small signal gain as a function of current density for a number of values of pump-field intensity for a 3-meter-long second-stage interaction region. The expected range of pump-field intensities and current densities attainable in a two-stage FEL experiment performed using the UCSB electrostatic accelerator is also shown. Small signal gain appears to be adequate to insure that lasing of the second stage will occur, providing the required values of current density and pump-field intensity are obtained. The energy spread and beam energy stability during the pulse must also be within the desired range. All of these parameters appear to be attainable.

Assuming that a two-stage FEL experiment is feasible using the UCSB electrostatic accelerator, a number of factors impose constraints on the design of the experimental system. A relatively long pump-field wavelength (on the order of 1 mm) is needed to achieve adequate second-stage bucket height, and the pump-field intensity must be high in the interaction region, which must be long and narrow. If we assume the pump field is confined in an open resonator cavity, the beam diameter at any point in the cavity can be calculated[3]. Assuming the pump beam diameter is a factor $\sqrt{2}$ larger than the minimum diameter a distance 5 meters from the beam waist, we obtain from the equations for a concentric cavity that the beam diameter would have to be 8 cm at the waist for 1 mm radiation. This would be too large to pass through the wiggler needed to produce the pump beam. If the beam intensity were 10^8 W/cm^2 at the waist, the power level in the cavity would be about 5 GW. For the intensity to be reduced to 10^4 W/cm^2 at the cavity end mirrors, the mirrors would have to be 3.5 m in diameter and would be located 220 m apart. This is clearly an unacceptable solution.

II. Approach being Taken

As part of our work for ONR we have developed a practical cavity design concept for a two-stage FEL. The design employs a waveguide to confine the pump field and produce a long, narrow, high-intensity pump beam in the interaction region, but permits the beam to expand by diffraction outside the

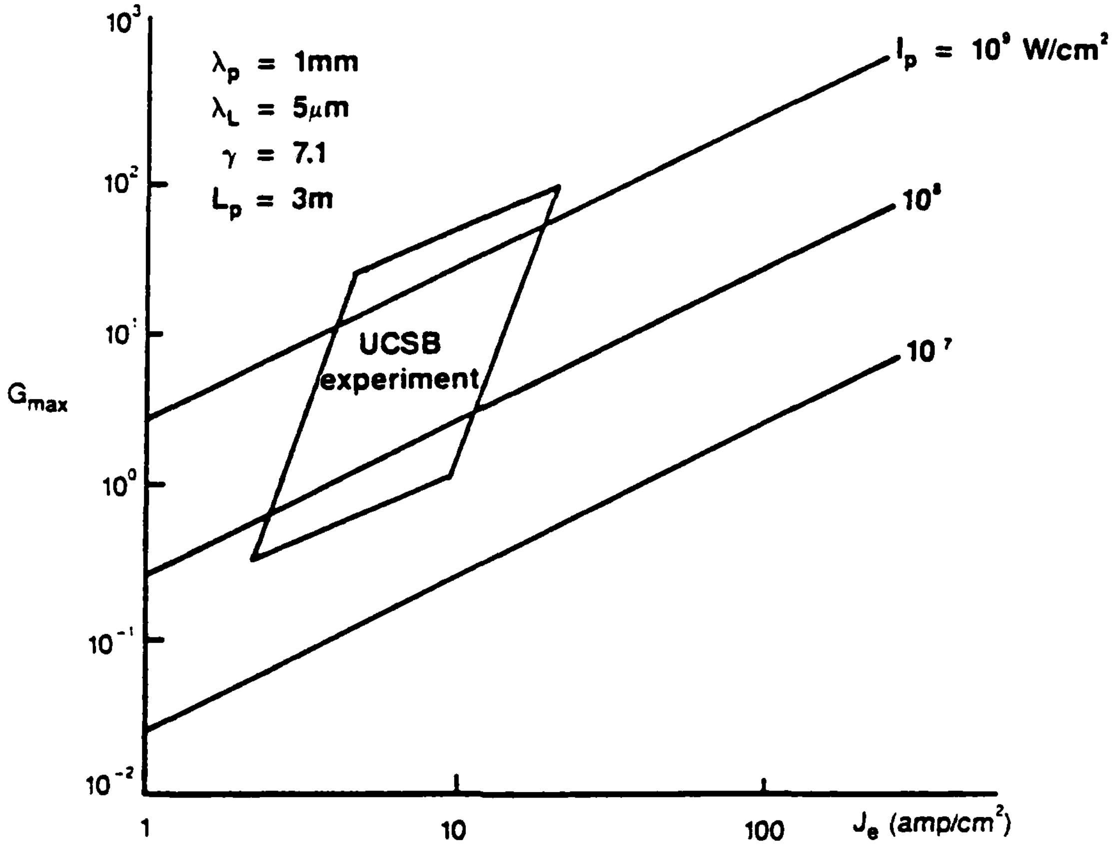

Figure 2. Second stage small signal gain as a function of current density for different pump-field intensities. Box shows the expected parameter range for a two-stge FEL experiment at UCSB.

waveguide to protect the cavity end mirrors. A schematic diagram of this quasioptical cavity design concept is shown in Figure 3.

This design has a number of unique features. It consists of a cylindrical waveguide and nested cavity end mirrors. One of the main problems that must be solved in a two-stage FEL is how to confine a high-intensity pump field in a very low loss cavity while simultaneously extracting the short-wavelength radiation. In the quasioptical cavity shown in Figure 3, the long-wavelength radiation leaving the waveguide will expand more rapidly by diffraction than the short-wavelength radiation, permitting holes to be placed in the centers of the long-wavelength-cavity end mirrors through which the short-wavelength radiation could pass without significant loss of long-wavelength radiation. The lowest loss waveguide mode in this cavity is the annular TE_{01} mode. Losses are minimal for this mode both at the wall of the waveguide and, after the beam expands into free space, at the holes in the end mirrors. The short-wavelength radiation, which also has an annular profile, will be contained in a separate cavity coaxial with the long-wavelength cavity. Part of the short-wavelength radiation will be extracted as output power. A unique feature of this design is that a helical wiggler is needed to fully excite the TE_{01} pump field waveguide mode.

The high quality electron beam entering the cavity would first pass through the second-stage interaction region, where short-wavelength radiation is produced. It then would pass through the first-stage interaction region, where a relatively large energy spread would be produced in the process of enhancing the long-wavelength radiation. After passing through the quasi-optical cavity the electron beam would be returned to the electrostatic accelerator. A modified quasioptical cavity design could be used if two separate electron beams were used to produce the long- and short-wavelength radiation.

To produce laser gain the pump, laser, and electron beams must overlap. This means that the electron beam must have a diameter large enough to overlap the region of peak intensity of the TE_{01} mode in the waveguide. The electrons contributing to laser gain would, therefore, be in off-axis orbits, and the existence and stability of such orbits and their ability to couple to the TE_{01} mode must be demonstrated if this approach is to prove feasible.

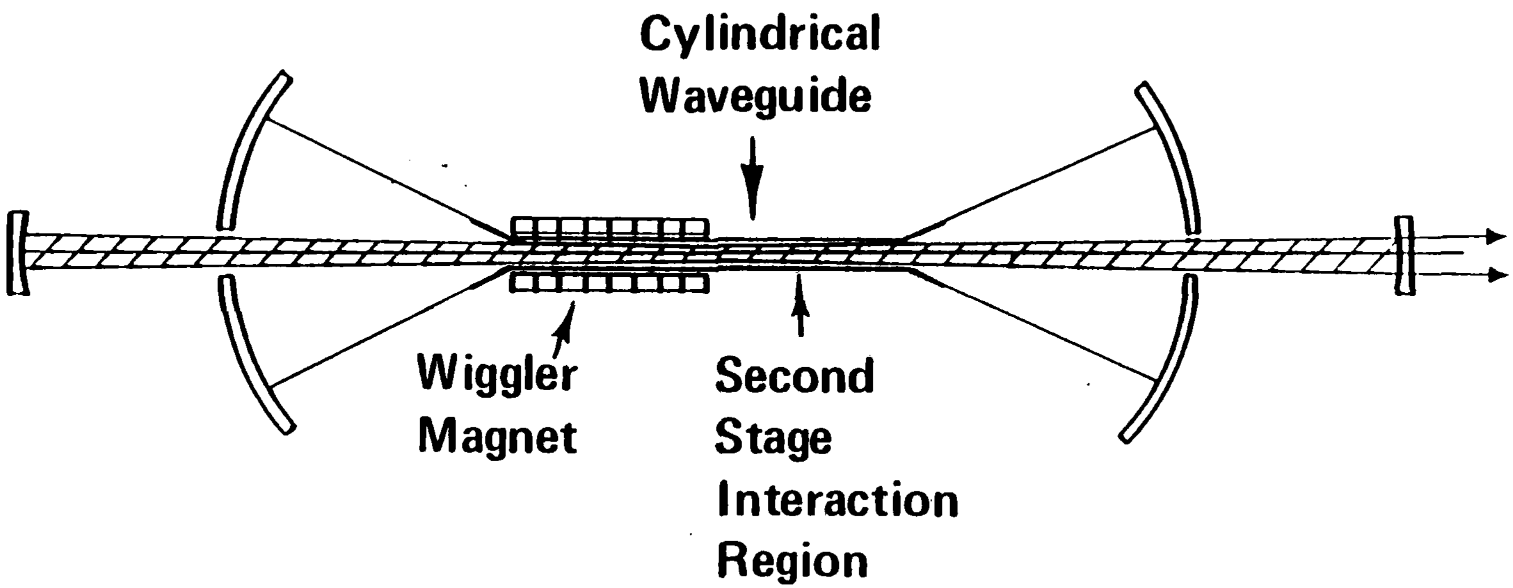

Figure 3. Conceptual design of the cavity structure for a two-stage FEL.

In the process of developing a design for a two-stage FEL experiment it was decided to preferentially pursue technologies which, if successful, could be scaled up to a practical, high-power, continuously operating laser. An alternative cavity design has been proposed by Elias, et al., that permits the use of a linear wiggler and a rectangular waveguide[4]. This system also has very low losses in the waveguide and the peak of the intensity pattern is on axis, permitting the use of a narrow on-axis electron beam. We believe this alternative cavity design is of interest for single-stage long-wavelength systems and may be capable of demonstrating two-stage operation in a proof-of-principle experiment on a pulsed basis, but that it will not be scalable to a high-power practical device.

Laser output power is directly proportional to conversion efficiency and to total electron current. In a constant period wiggler the amount of electron energy converted to photon energy is never greater than the bucket height. Conversion efficiency in an FEL with a magnetic wiggler can be increased by tapering the wiggler. For an electromagnetic pump field this same efficiency enhancement could be achieved by applying an axial electric field in the interaction region. A solid waveguide is, however, an equipotential surface, which would seem to prevent the introduction of axial electric fields. Segmenting the waveguide to produce a static axial field in the inside volume would prevent propagation of waveguide modes that require axial wall currents. Cylindrical TE_{0N} modes, of which the lowest loss mode is the TE_{01}, have only azimuthal wall currents and could propagate in such a waveguide. These appear to be the only waveguide modes that could be used if efficiency enhancement is desired in an FEL with an electromagnetic pump field.

The long-wavelength FEL cavity being developed by Elias, et al., cannot be segmented to produce an axial electric field while still propagating the desired waveguide mode, and, therefore, will be incapable of producing enhanced second-stage gain. Transmission of short-wavelength radiation out of their cavity would be accomplished by using a grating or hologram, which deflects the short-wavelength radiation to a separate short-wavelength-cavity end mirror but does not affect the long-wavelength radiation. The major problem with such an approach is that the grating or hologram must be located precisely in the region of highest intensity of the long-wavelength radiation.

Survival of the deflector in a continuously-operating high-power system is doubtful, although it probably would work in a lower-average-power, pulsed, proof-of-principle experiment.

The quasioptical cavity structure we are proposing requires a helical wiggler. Possible wigglers that could be used are wigglers employing high current copper coils[5,6], a superconducting helical wiggler[7], or a permanent magnet helical wiggler[8]. Permanent magnet wigglers have been found to be relatively simple and practical devices, and practically all experiments employing linear wigglers use permanent magnet or hybrid steel-permanent-magnet structures. We believe that two-stage FEL's of the type we are proposing would be more practical if a permanent magnet wiggler were employed in the first stage. A goal of this project has therefore been to develop a permanent magnet helical wiggler for the proposed two-stage FEL experiment.

In conclusion, we believe that our conceptual design for a two-stage FEL experiment incorporating a quasioptical cavity and a permanent magnet helical wiggler is a practical solution to the design of a two-stage FEL and is the only proposed design which, if successful, could be scaled to a useful high-power device.

III. Progress during this past year

During FY-84 we have devoted our efforts to developing hardware to test the concept of a quasioptical-cavity FEL employing a permanent-magnet helical wiggler. This includes both design work for the UCSB experiment and experimental work at KMSF to establish a capability for investigating quasioptical cavities and magnetic structures.

Magnetic wiggler design

As part of this program we developed an analytic model of a permanent-magnet helical wiggler based on the Halbach design. The Halbach helical wiggler consists of an array of permanent-magnet dipole rings that are rotated relative to each other to produce a twisted helical field in the clear through volume. In FY-84 we extended the analytic model to include more general magnet configurations that might be capable of producing a helical field either with less magnetic material or with less field distortion than the Halbach model. These configurations would, however, be less flexible than the Halbach design.

We have also developed a computer program, based on the analytic models, that calculates the field inside a helical wiggler and compares the field produced by a given magnet configuration with that of an ideal helical wiggler. Figure 4 shows the results of a calculation for a Halbach wiggler with 8 magnets per dipole ring and 8 dipole rings per period. The figure shows the relative deviation of the field produced by this wiggler from that of an ideal helical wiggler with the same on-axis field. The period of the wiggler was assumed to be 10 cm. Within a radius of 1 cm from the axis, the deviation of the field from that of an ideal helical wiggler is found to be less than one percent. The waveguide we intend to use in this experiment would have an inner radius of 1.22 cm and the electron beam would be confined to a region less than 1 cm in radius, so such a design could be adequate for the proposed experiment.

The analytic model we are using does not include end effects. These end effects can be handled by existing magnet design codes. During this contract period we have acquired the two-dimensional magnet design codes POISSON and PANDIRA and the three-dimensional magnet design code GFUN. The two-dimensional codes have been used to obtain qualitative information that can assist in the magnet design, but a three-dimensional code is needed to fully solve the problem. Our efforts this year have been concentrated on modifying the GFUN code to make it a more useful tool for helical wiggler calculations. Modifications have been made to permit the code to more quickly calculate the case of the infinite helical wiggler, so that GFUN can be compared with the results of our analytic model. Additional modifications are presently being made to increase the speed of the code by about an order of magnitude using an improved iteration procedure developed by J. E. Pasciak of Brookhaven National Laboratory.[9] By the end of the present contract period we expect to have a comprehensive computer capability for helical wiggler design, and we expect to upgrade this capability even more during the proposed contract.

In order to build a helical wiggler magnet we must have a laboratory facility where we can calibrate the individual magnet pieces. We must also be able to assemble the pieces into a wiggler and measure the field of the entire structure. During the current contract period we completed the design for this laboratory and began ordering equipment. The laboratory will include a large electromagnet used for calibration of Hall probes and rotating coil

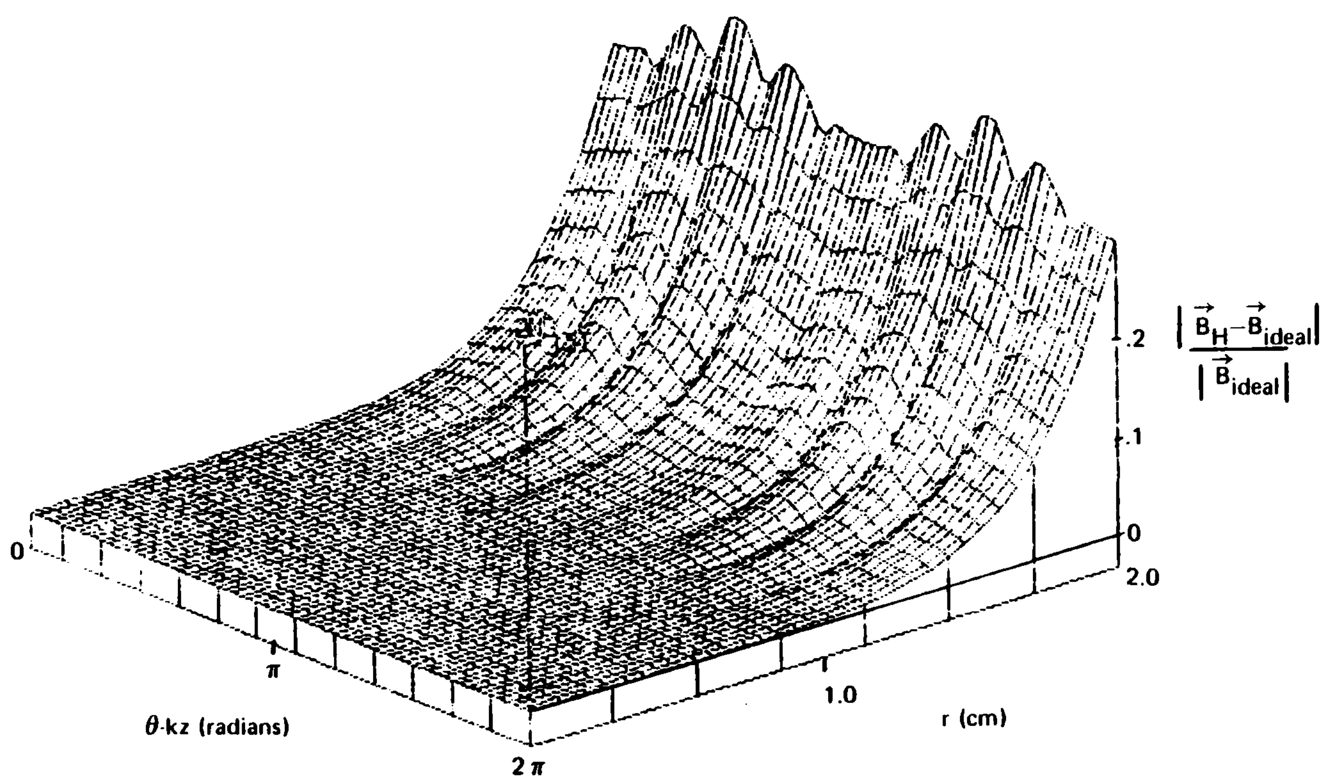

Figure 4. Relative deviation of the magnetic field from a Halbach-type helical wiggler from an ideal helical wiggler for a wiggler with 8 magnets per dipole ring and 8 dipole rings per period..

detectors, an NMR system to calibrate the large magnet, precision Helmholtz coils for calibrating individual magnet pieces, and positioning stages both for detectors and for wigglers and wiggler subsections. Measurements will be taken with automated equipment interfaced to a PDP 11/23 computer.

Beam Transport Studies

Assuming a permanent-magnet helical wiggler is developed for this experiment, it must be demonstrated that an electron beam can be propagated through the wiggler in such a way that it interacts with the TE_{01} waveguide mode and produces adequate gain to operate a high-power long-wavelength FEL. It must also be demonstrated that the electron beam can be recovered after leaving the wiggler for operation in an electrostatic-accelerator FEL.

Not only will this be the first FEL experiment employing a permanent-magnet helical wiggler, it will also be the first experiment employing a large-diameter beam in a helical wiggler in which good control over electron orbits and virtually complete beam recovery will be required. It is, therefore, important that we have a detailed understanding of the possible electron orbits and the interaction of the electron beam with the laser beam in the wiggler.

To study electron orbits in the wiggler we have developed a three-dimensional simulation code that can simulate the motion of a beam of electrons through a three-dimensional magnetic structure. The code is based on an electron trajectory code obtained from Brookhaven National Laboratory, but it has been considerably upgraded to include calculation of spontaneous emission and the self consistent interaction of a beam of electrons with an arbitrary waveguide or free-space mode.

The first question that had to be answered was whether stable off-axis electron orbits existed that could transfer energy to the TE_{01} mode. Large stable helical orbits were shown to exist by Diament[10], but these orbits have zero net coupling to the TE_{01} mode. Continued investigation showed that two other classes of orbit existed that were both stable and coupled well to the desired waveguide mode. A projection of these orbits in the transverse plane of the wiggler is shown in Figure 5. We have determined the initial conditions at injection required to establish these orbits and have investigated the stability of these orbits to small perturbations of the initial conditions

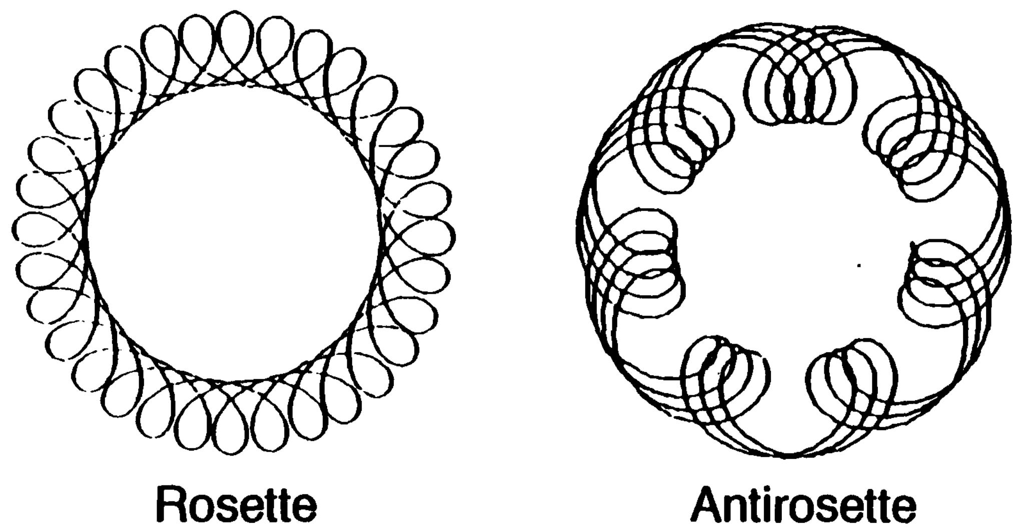

Figure 5. Transverse projection of two stable off-axis electron orbits that interact with the TE_{01} waveguide mode. The figures were obtained from a computer simulation of electron trajectories in a helical wiggler.

from their ideal values. The results of these studies showed that electron orbits of this type would be suitable for the system we are proposing, with the rosette type orbit being the easier to establish.

The initial conditions require the electrons entering the wiggler to have a specified value of the magnitude and direction of the transverse component of the electron velocity, $\vec{\beta}_{\perp}$. The value of $\vec{\beta}_{\perp}$ must vary in a prescribed way across the face of the beam. This is shown in Figure 6. It appears that the desired velocity distribution can be established by passing the electron beam through a cusp-like field before it enters the wiggler. The detailed design of the cusp-wiggler interface will be one of the important design tasks that will be undertaken during the next stage of this project.

We have calculated the spectrum of spontaneously emitted radiation from electrons passing through the wiggler in off-axis rosette orbits. The spectrum shows a sharp clear peak at the expected fundamental frequency as well as a series of much lower intensity higher harmonics and subharmonics. We wish to diagnose the harmonic emission as part of the proposed experiment for two reasons. First, it may prove to be an important technique for diagnosing the electron beam, and second, the measurement will provide data that could be used in future experiments to try to produce lasing directly on one of the higher harmonics of the fundamental frequency.

We have just begun to study the interaction of a beam of electrons with the laser beam. These initial studies indicate that the laser gain that can be achieved is within about a factor of 2 of the gain calculated using a simple one-dimensional FEL simulation. The three-dimensional studies also demonstrate the expected periodic bunching on the scale of the laser wavelength. Up to now calculations have only been performed using filamentary off-axis electron beams. In future work we will develop more realistic representations of a three-dimensional electron beam. We are presently studying techniques for doing this with a minimum number of electrons in the simulation.

Cavity design studies

The quasioptical cavity is designed to be a very low loss cavity for the long-wavelength radiation. Cavity end mirrors can be made sufficiently large

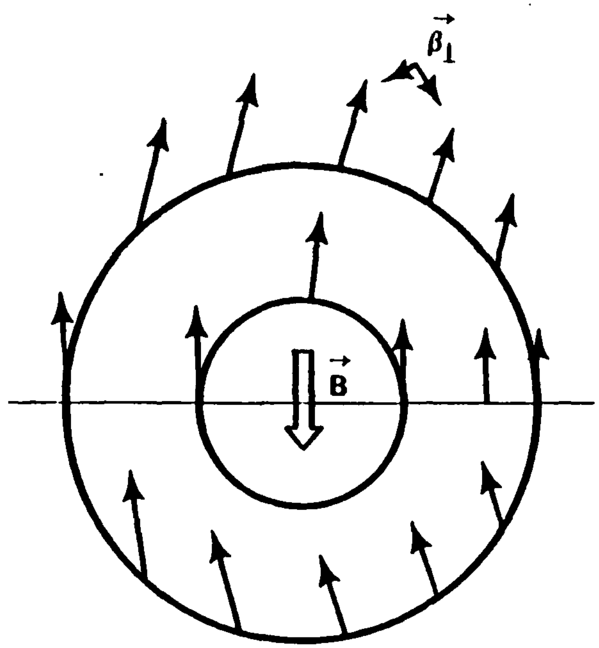

Figure 6. The injection conditions for establishment of rosette orbits for all electrons in the beam require that $\beta_\perp$ vary in magnitude and direction is a prescribed way across the face of the beam. Such a distribution may be produced by a cusp-like field located at the entrance to the wiggler.

so that diffraction losses around the outside edges of the mirrors are arbitrarily low. Also, by moving the mirrors sufficiently far back from the end of the waveguide, losses of long-wavelength light from the holes in the centers of the mirrors can be made arbitrarily small while still permitting transmission of second-stage light. In the proposed experiment we expect to use mirrors 0.9 meters in diameter located 2.5 meters from the ends of the waveguide.

The dominant loss mechanism expected in this cavity would be due to mode conversion losses at the waveguide-free space interface. After studying this problem we have concluded that these losses could be virtually eliminated by properly designing the cavity[11]. If this is done the major source of cavity loss would be absorption losses on the surfaces of the metal mirrors. Cooling the mirrors could reduce these losses.

In the first experiment we do not intend to cool the mirrors and will not try to completely eliminate mode conversion losses. The objective of the first experiment will be to demonstrate and study the operation of the quasi-optical cavity, and an experimental configuration that provides a maximum amount of information about the operation of the cavity is desired.

To obtain information on quasioptical cavity operation and on the importance of various loss mechanisms we have set up a test cavity system using standard microwave sources in our Ann Arbor laboratory. A schematic of the laboratory experiment is shown in Figure 7. TE_{01} radiation produced by the microwave system, is expanded using a specially designed waveguide taper into half of a quasioptical cavity through a partially transmitting cavity coupler. The Q of the cavity is determined from the width of the cavity resonance as a function of frequency. Cavity Q's in the range of 10^2 to 10^7 can be measured. From the change in cavity Q produced by different cavity configurations, losses from various loss mechanisms can be determined.

Our studies during the present contract period determined the contribution to the width of cavity resonances of various cavity couplers. After experimenting with a number of different thin film and mesh couplers, sharp narrow cavity resonances have been obtained using precision etched metal meshes with submillimeter mesh constants (see Figure 8). Studies of the various cavity loss mechanisms are now under way.

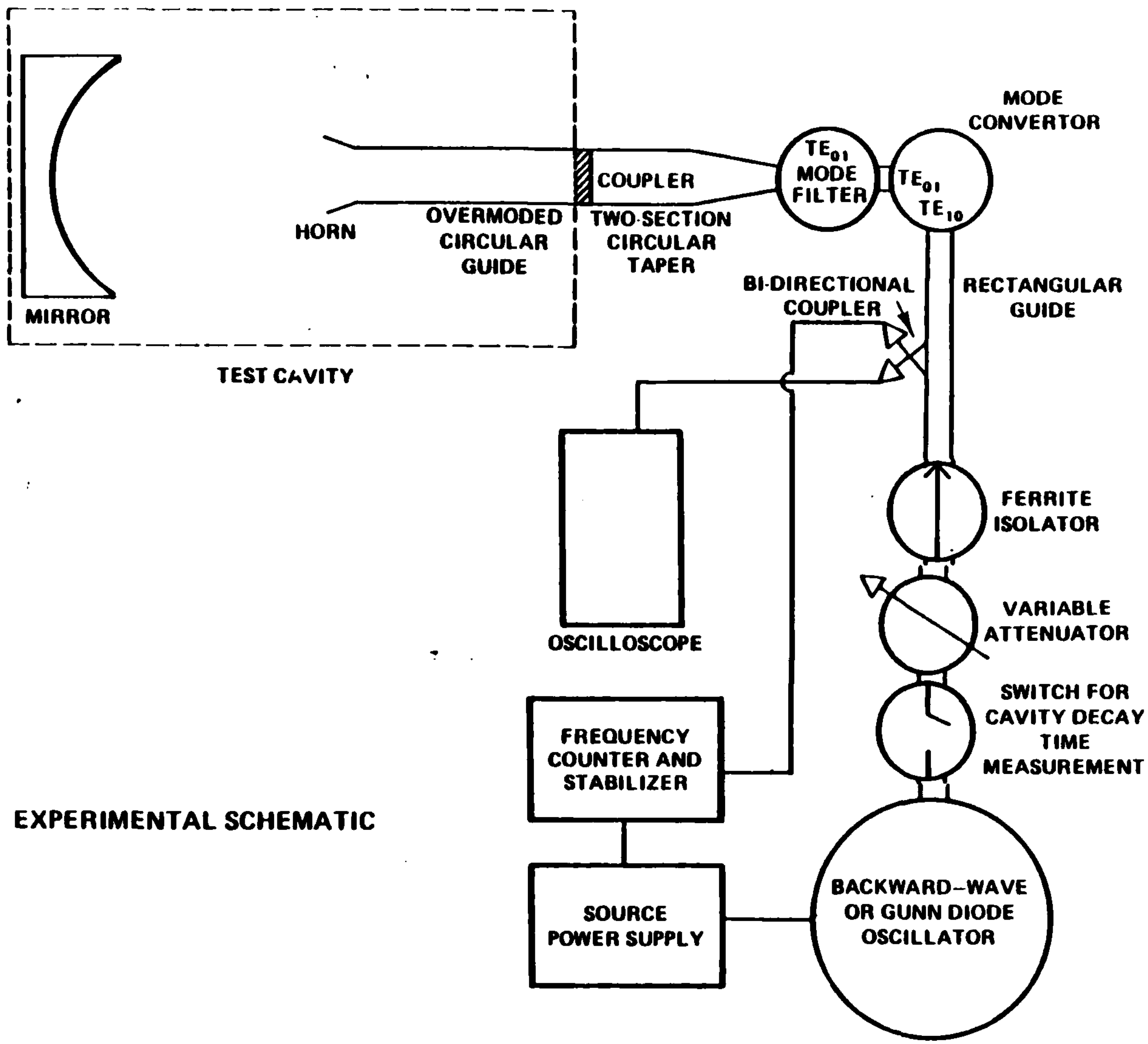

Figure 7. Schematic of quasioptical test-cavity experiment now operating at KMS Fusion.

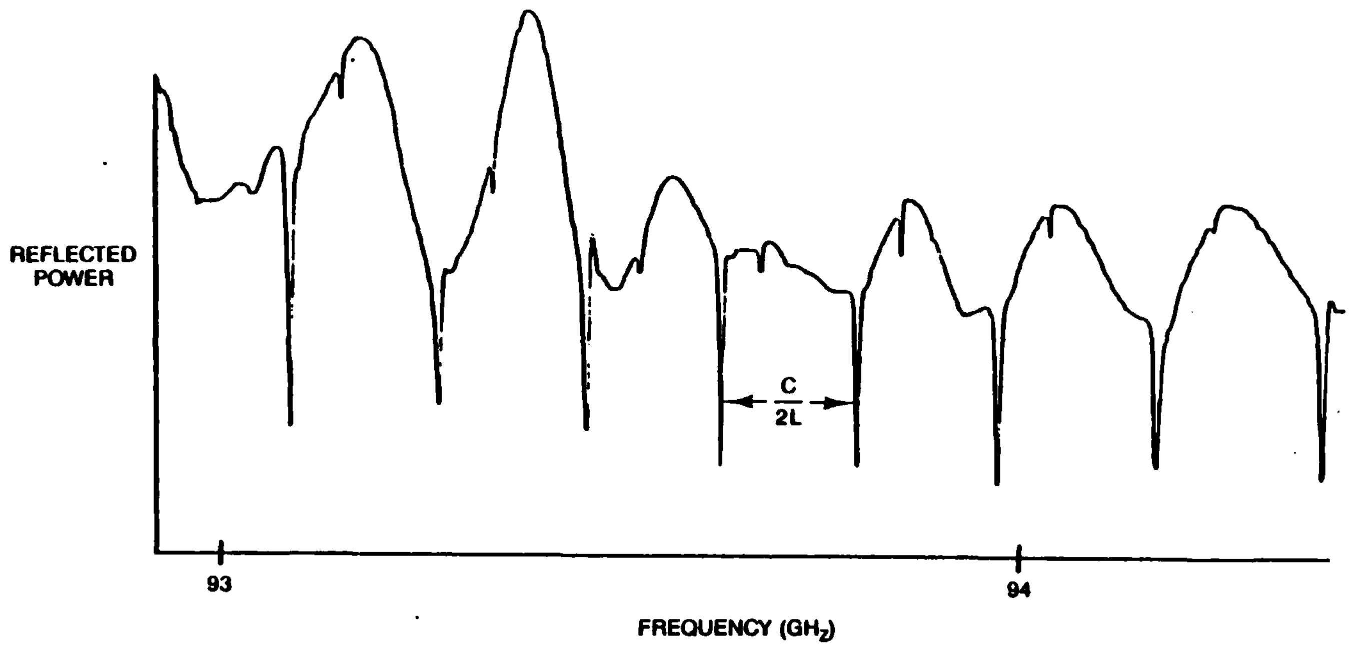

Figure 8. Reflected power as a function of microwave frequency for TE_{01} cavity resonances obtained using a metal mesh coupler with a 500 μm mesh constant. The regular spacing, uniform appearance and large amplitude of the cavity resonances indicate efficient TE_{01} excitation.

First-stage quasioptical cavity experiment

As a continuation of the work we have performed up to this point, we are planning to perform an experiment to demonstrate operation of the first-stage quasioptical cavity. This would be the first step in a series of experiments leading up to demonstration of two-stage FEL operation. A schematic of the planned experiment is shown in Figure 9. Parameters of the planned experimental system are:

wavelength of radiation	10^{-3} m
length of wiggler	2 m
period of wiggler	0.1 m
length of the waveguide	5 m
inside diameter of waveguide	2.4×10^{-2} m
distance from end mirror to waveguide	2.5 m
diameter of mirrors	0.9 m

For this experiment we would use a two-mirror configuration on one end of the cavity to facilitate diagnostics. The radius of curvature of the spherical mirror in the two-element configuration is about twice the radius of curvature of the single spherical mirror on the other end of the cavity. Radiation leaving the waveguide would be reflected from the spherical mirror in the two-element configuration into a near-parallel beam. A flat mirror would be placed at the beam waist for the larger-diameter beam, so that the long-wavelength radiation would be reflected back onto itself after striking the flat mirror. The flat mirror would be made partially transmitting to diagnose the radiation in the cavity.

It has been shown that a two-mirror configuration of this type could be used to virtually eliminate mode conversion losses at the waveguide-free-space interface,[11] which is an important consideration for operating the cavity at high intracavity power levels. The experiment we are planning is primarily intended to demonstrate production of the desired radiation pattern and successful functioning of the wiggler and beam optics. This can be done at relatively low power and low current. Extension of the operating regime of the first-stage to high power and high current would be the next step following this experiment.

Diagnostic instrumentation would be placed behind the partially-transmitting flat mirror to determine the intensity, polarization, and spectral distribution of radiation in the cavity. Intracavity power levels of at least 10^4 - 10^5 watts are expected in this experiment, which should permit diagnostic measurements to be easily made. The electron beam is expected to be on for several microseconds, so that time resolved measurements of the beam evolution are also possible.

The large spherical mirrors shown in Figure 9 would be manufactured in two sections. If the electron beam were to inadvertently damage one of the mirrors in the course of the experiment, it would be possible to replace the inner section of the mirror without having to replace or refinish the entire mirror. Metal apertures would be placed in front of the mirrors during the initial process of directing the beam through the cavity, but they could not be placed in the cavity during laser operation. We, therefore, feel this would be a prudent design for the large spherical mirrors.

Spontaneous emission at higher harmonic frequencies is generally low for a narrow on-axis electron beam in a helical wiggler. In our case, most of the radiation would be produced by off-axis electrons, and the amount of higher harmonic radiation observed on axis is expected to be much greater for these orbits. The higher frequency radiation would be diffracted less than the fundamental, and it should be possible to observe this radiation through the hole in the cavity end mirror. An additional spectrometer would, therefore, be placed in back of one of the cavity end mirrors to observe this radiation.

Since the waveguide and wiggler would be open only at the ends, diagnosing the electron beam inside the wiggler could be difficult. Before the laser begins operating, we could observe the position of the electron beam in the waveguide by means of a fluorescent screen. The screen would be mounted on a hollow cylindrical piston that could slide along the waveguide. The spot on the screen could be observed by means of a telescope looking along the axis of the wiggler.

After laser operation begins, no obstructions could be placed in the waveguide. It may be possible to determine if and where electrons are being lost to the wall using a segmented waveguide rather than a continuous conducting pipe. As mentioned previously, a carefully designed segmented waveguide should not significantly disturb propagation of the TE_{01} mode.

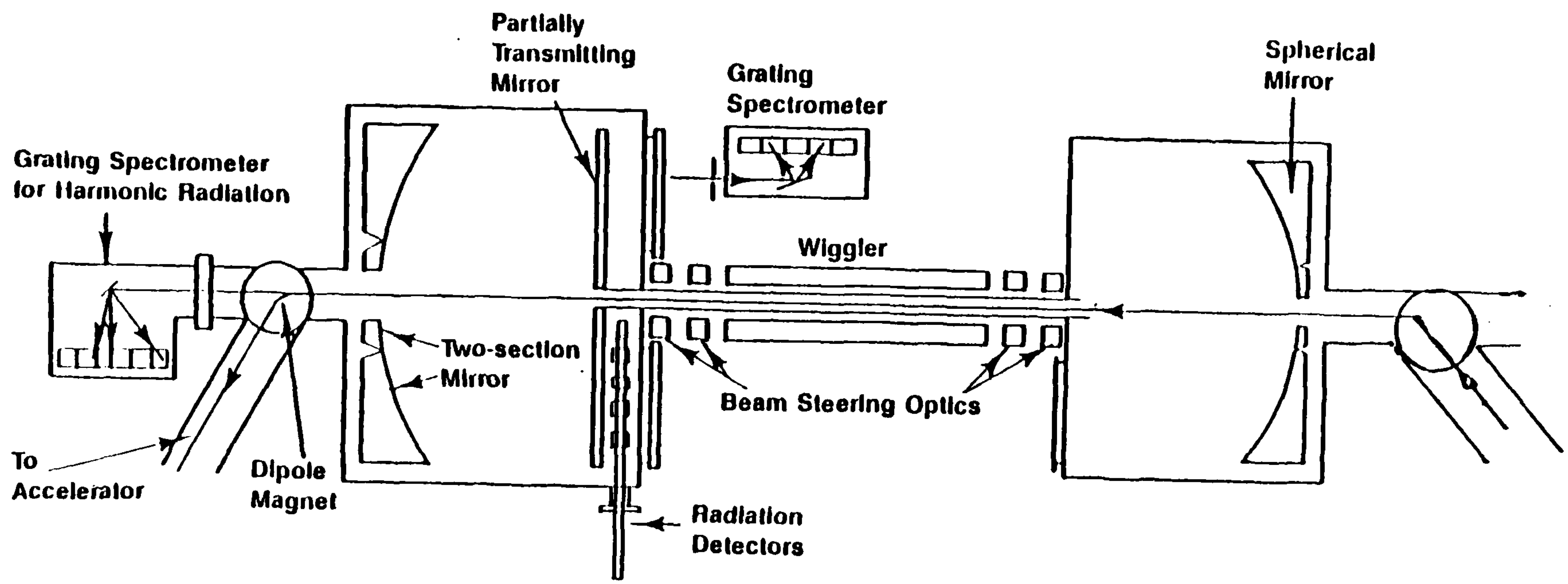

Figure 9. Schematic diagram of the proposed first-stage FEL experiment to be conducted at UCSB.

Electron diagnostics already available on the UCSB system would be used to characterize the electron beam before and after it passes through the cavity structure.

The experiment we are planning would characterize the operation of a long-wavelength quasioptical-cavity FEL at intracavity power levels and beam currents lower than those required for two-stage operation. Once low-power operation has been demonstrated, the next step in the program would be to make the necessary modifications to the wiggler and accelerator system to attain high-power first-stage operation.

The progress that has been made over this past year has brought us closer to our goal of demonstrating a two-stage free electron laser. We have improved our models of the wiggler and the electron orbits in the wiggler. We have developed a laboratory in which quasioptical cavities can be simulated, and we have developed an experimental plan for testing the operation of the first stage of the FEL. The next phase of this project would be construction of the hardware and operation of the first-stage experiment.

IV. List of Recent Publications

1. S. B. Segall, H. Takeda, S. Von Laven, P. Diament, and J. F. Ward, "The KMS Fusion, Inc. Two-Stage FEL Program", in SPIE 453, Brau, Jacobs, and Scully eds, page 178 (1984).

2. H. Takeda and S. B. Segall, "Limiting Energy Spread at High Laser Intensities Using Phase Space Displacement", ibid. page 196.

3. S. Von Laven, S. B. Segall, and J. F. Ward, "A Low Loss Quasioptical Cavity for a Two-Stage FEL", ibid. page 244.

4. S. B. Segall, S. Von Laven, M. S. Curtin, and H. Takeda, "Design of a Millimeter-Wavelength FEL Experiment Employing a Large-Diameter Electron Beam and a Quasioptical Cavity", 1984 FEL Conference, to be published in Nuclear Instruments and Methods (1985).

5. H. Takeda, S. B. Segall, P. Diament, and A. Luccio, "Stable Off-Axis Electron Orbits and their Radiation Spectrum in a Helical Wiggler", ibid.

6. M. S. Curtin, S. B. Segall and P. Diament, "Design of a Large-Acceptance-Volume Permanent-Magnet Helical Wiggler", ibid.

7. P. Diament, "Helical Wiggler Design with an Array of Uniform, Small Permanent Magnets", ibid.

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10. P. Diament, Phys. Rev. A 23, 2537 (1981).

11. S. Von Laven, S. B. Segall, J. F. Ward, SPIE 453, 244 (1984), Brau, Jacobs and Scully eds.

October, 1984

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